Neutrino Physics and the Cosmology/Astrophysics Connection: Key Opportunities

For each section in the writing plan, we include some of the points that arose during working group discussions. This is not complete, and not especially carefully written up, and comments are welcomed. This information from the group is being provided to the lead writers for each section (noted below), for their consideration.

General points of high importance: make the open scientific questions especially clear, briefly cover past successes for context, make connections to other physics issues, and *motivate new experiments and observations.*

1. Origin and nature of the cosmic rays **(Todor Stanev @ Bartol)**

   How can observations of high energy neutrinos tell us more about cosmic rays, especially those at the highest energies?

   A particularly important point is that the fluxes of 10^{20} eV protons, 10^{18} eV neutrinos, and 10^{10} eV gammas are connected. This has been nicely shown by Semikoz and Sigl, as well as several other authors.

   Excellent experimental progress is expected on all three of those fronts in the near future, and especially for these GZK neutrinos. The predicted neutrino flux has a (debatable) minimum value, and it is worth asking how far that should be chased experimentally. Given the importance of finding them, future experiments should be strongly motivated.

   If the GZK cosmic ray cutoff is not seen, that could be good news as new physics. If it is seen, then the more protons that were attenuated, the more GZK neutrinos are expected, which is also good news.

   The GZK neutrino flux predictions do depend on the UHE cosmic rays being primarily protons, as opposed to nuclei, photons, or exotica. Thus the search for the GZK neutrinos provides complementary information on the composition argument.

   Another key issue is of course the acceleration mechanism for the highest energy cosmic rays. It is important to understand what sources, astrophysical or exotic, could produce the highest energy particles in the universe. This is closely connected to the question of the redshift distribution of sources. If the sources are astrophysical, then we are probing nature's best accelerators, and there are interesting connections to astronomical observations. If they are exotic, then we would learn about the decay of supermassive dark matter, topological defects, etc., which would be of great interest for particle physics. Related to the source question is the angular distribution of the detected events. The highest energy protons may point back to their sources, and the GZK neutrinos will too.

   The neutrino experiments required to test these "standard" GZK scenarios also test a variety of exotic scenarios, e.g., Z-burst, top-down models, and more generally the energy frontier in particle energies.

2. GZK neutrino detection and new physics above a TeV **(Doug McKay @ Kansas)**

   How well can the searches for the GZK neutrinos test for new physics above the TeV scale?

   The GZK neutrinos are so energetic that their detection cross section on nucleons would probe center of mass energies in excess of a TeV. The present limits on the GZK flux actually limit a product of the flux and cross section. Since there are lower bounds on the flux (using the proton and gamma data) and the cross section (the standard electroweak theory), these limits can be interpreted as limits on enhancements to the cross section due to new physics. Already, even with relatively weak observational limits on the flux, the scale of new physics probed is at the energy frontier, and competitive with collider bounds.

   For example, the best limits on large extra dimensions come from neutrino data (supernovae for small n, GZK neutrinos for large n). The importance of neutrinos in covering all n should be emphasized.

   The most important thing is that the sensitivity to the GZK neutrinos could be very much improved. Existing plans take important first steps, but may not be enough. How far should this detection be "chased," if initial experiments yield only limits? Also, different experiments sample the GZK spectrum at a range of neutrino energies, and pushing to the highest observable energies has important consequences for testing new physics.

These tests of new physics are in a "survey" mode, and are a very important complement to controlled experiments at colliders, e.g., the LHC. Can this argument be better developed, in terms of specific types of new physics models?

This and all astrophysical neutrino fluxes must ultimately be measured and understood, to have better sensitivity to new exotic sources of neutrinos, e.g., related to dark matter models. Dark matter is one of the key indications of physics beyond the standard model, and it is essential to have a wide variety of ways of testing it.

3. Neutrino probes of high energy astrophysical sources **(Peter Meszaros @ Penn State)**

   How can observations of high energy neutrinos reveal the physics of high energy astrophysical objects such as AGNs and GRBs?

   First, we know from a variety of astronomical observations that these sources involve tremendous energies in small volumes (and in the case of GRBs, also operating on very short timescales). Second, also know that they produce very high energy gamma rays. Third, they are also candidate sites for high energy cosmic rays.

   The details of the physics and astrophysics of these objects remains mysterious, and neutrinos are a very important clue for making further progress. Unlike cosmic rays, neutrinos are directional, and unlike gamma rays, neutrinos are not attenuated by intergalactic radiation fields.

   A key issue is that the present generation neutrino experiments will be the first to have a realistic chance of seeing these sources. It won't be easy, but it will be a chance. IceCube has much better chances, and it is a very high priority to complete it. How much further might we eventually need to go to see more than just "first light," in terms of future experiments?

   Present models for these sources are much more reliable than in the past because we have so much more data now. A recent AMANDA paper nicely makes the point that their neutrino flux sensitivity is comparable to the observed gamma ray flux from a specific AGN. If the gamma rays come from neutral pion decay, with the pions produced by nucleon-nucleon or nucleon-photon collisions, then comparable fluxes of neutrinos from charged pion decays are expected. It is presently unknown how the gammas are produced, and thus the neutrinos are a very important test of the details of the sources.

   There is a lot of skepticism in the high energy community about the AGN neutrino flux predictions, mostly because of past predictions that were very high, and which were not seen in Soudan, MACRO, etc. To what extent is this complaint justified, or should it be recognized as progress in terms of eliminating models? How much more reliable are the model predictions today, particularly those connected to the gamma data?

   Essential connection between IceCube type experiments and GRB observations with SWIFT, etc., and AGN observations with VERITAS, etc.

   In order to search for new physics, it is essential to understand neutrinos from these "conventional" high energy neutrino sources. First, we may be able to make novel tests of neutrino properties, e.g., neutrino decay would change the flavor ratios from the expected $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$. Second, understanding the sources better may help set new particle physics limits, given the extreme physical conditions in the sources, and a comparison might be made to the Sun and supernovae (i.e., how important they are as "understood" sources). Third, as we build up a holistic picture of what produces the cosmic ray, gamma, and neutrino backgrounds, we will improve the sensitivity for looking for new physics sources which can contribute to those; for example, how much can dark matter decay or annihilation contribute to the EGRET diffuse gamma ray background? How might that change given a better holistic picture? It should be noted that the gamma background from 1 MeV and up provides important constraints on models of large extra dimension, e.g., Hall and Smith, Hannestad and Raffelt, and many others.

4. Dark matter searches using neutrinos **(Jonathan Feng @ Irvine)**

   What unique role can neutrinos play in identifying the particle nature of the dark matter?

Using neutrinos certainly doesn't sound easy, but the other approaches are challenging too, and this is one of the most important questions in particle physics (and also in cosmology).

Since we don't yet know what the dark matter is, we have to explore all options. Even in SUSY scenarios, collider, direct, and indirect bounds play complementary roles. More importantly, in more general scenarios, how do these different approaches compare in their ability to probe new territory?

The obvious scenario is heavy WIMPs being captured by the Sun or Earth, with neutrinos being among their eventual annihilation products. For WIMPs above 100 GeV, the solar signal depends on simultaneously taking absorption, neutrino mixing in matter, and vacuum oscillations into account (the only full treatment of those effects was by P. Crotty). How could such searches be improved, and how important is that?

As indicated in the previous section, understanding the astrophysical neutrino sources or more generally the high energy accelerators like AGNs and GRBs is an important step. Beyond that, new anomalous neutrino sources may be recognized.

The possibility that neutrino mass and dark energy may be connected (e.g., Fardon et al.) is also intriguing and should be mentioned.

5. NEUTRINOS AS A PROBE OF SUPERNOVAE **(Tony Mezzacappa @ Oak Ridge)**

How can the observation of a supernova neutrino burst reveal the mysteries of how core-collapse supernovae work?

Core-collapse supernovae are among the most extreme astrophysical environments, and their understanding depends crucially on details of astrophysics, general relativity, nuclear physics, and particle physics. While they are observed frequently by astronomers, and there is no doubt that they explode in nature, in the most modern numerical simulations, with the best physics, they do not, since the outgoing shock is insufficiently energetic to eject the stellar envelope.

The proto-neutron star conditions are a total energy of 10^{53} ergs, near nuclear densities, temperatures of 10s of MeV, and timescales of seconds. In contrast, in the envelope, the explosion energy is 10^{51} ergs and takes hours. Neutrinos have a unique ability to reveal the extreme conditions in the proto-neutron star directly, and are a key to everything.

Supernovae in our Galaxy can be easily detected by the existing large detectors like SK, SNO, KamLAND, LVD, etc. (and also by AMANDA and eventually IceCube in the mode of a statistically significant increase in the large noise rate). These detectors were built for other purposes. Since detectors at the > 1 kton scale will not be built to only wait for a supernova burst (since the rate is about a few per century), a high priority should be placed on running these detectors as long as possible, and with a high uptime fraction. Also, they should be linked into SNEWS. The importance of detecting supernova neutrinos should also be kept in mind in the design of future large detectors for other purposes, e.g., nucleon decay or long-baseline experiments (Hyper-Kamiokande or UNO would be able to detect supernova in nearby galaxies, though with few events per burst).

Regarding detection, the water or oil based detectors will do very well on $\bar{\nu}_e$, fairly well on $\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$, and not very well on ν_e. Better sensitivity on ν_e, while hard to achieve, is very important. From even the ~ 10 events from SN 1987A, we learned a great deal: these data established the total energy release, the average neutrino energy, and the duration of the pulse. The average energy of ~ 10 MeV and the long timescale, about 10 s, both support the idea of neutrino diffusion in the dense proto-neutron star. If it were not opaque to neutrinos, their average energies would be 10 times higher and the timescale just a few milliseconds. With the next supernova, $\sim 10^4$ events, mostly $\bar{\nu}_e$ are expected, and these can be used to test the energy spectra, time profile, etc., in detail.

Existing detectors will also have some sensitivity to the prompt ν_e burst. We really need something at the UNO/HK scale for that. Why is it so important astrophysically?

Besides direct detection of a burst, numerical modeling of the explosion is extremely important and touches many areas of frontier science.

The extreme conditions of the explosion are one of the few places in which neutrinos are the dominant actor.

The explosion or lack thereof is also connected to uncertainties in the nuclear equation of state, which is of fundamental importance.

Lots of possible new astrophysical connections: formation of the elements, rotation and magnetic fields, connection to GRBs, pulsar kicks and gravitational wave observations, etc.

6. Supernova neutrinos as tests of particle physics **(George Fuller @ San Diego)**

   With a better understanding of supernovae, how can tests of neutrino properties or tests of new physics be improved?

   The very sparse SN 1987A data have played an invaluable role in testing a wide range of new physics scenarios, for example by constraints on novel energy loss channels. Those arguments were good at the $\mathcal{O}(100\%)$ level, due to the low statistics and our incomplete understanding of supernovae. With data from a new Galactic supernova, tests could be made at the $\mathcal{O}(1-10\%)$ level.

   The strongest constraints on large extra dimensions come from supernovae for small n and from GZK neutrino limits for large n.

   The questions surrounding the possibility of sterile neutrinos are manifold, and are among the most important questions in neutrino physics, because the implications could be so profound. Connection to LSND and MiniBooNE for laboratory tests.

   While the solar and atmospheric neutrino mixing angles have been measured, and are large, the remaining one, θ_{13} only has weak limit of about 10 degrees. The unknown mixing matrix parameter U_{e3} plays only a minor role for solar neutrinos due to the large associated atmospheric δm^2 and the fact that θ_{13} is small. It is also very hard to see its effects in atmospheric neutrinos. However, it is of extremely high importance, since the size of U_{e3} controls the size of observable CP-violating effects in the neutrino sector. The experimental program to measure U_{e3} and the sense of the hierarchy (normal vs. inverted) at reactors and with long-baseline accelerator neutrinos is very difficult and will take a long time.

   However, due to the high matter densities, U_{e3} does play a very important role in MSW neutrino effects in a supernova, and these effects can be revealed through observing a Galactic supernova. The sense of the hierarchy also plays a key role. If the supernova model uncertainties can be reduced, and if a supernova is observed, these data may provide an important constraint on these unsolved questions in the neutrino sector. Also, there is sensitivity to U_{e3} via neturino oscillation effects in Earth; multiple detectors are needed.

7. Diffuse supernova neutrino background **(Terry Walker @ Ohio State)**

   How can detection of the diffuse supernova neutrino background constrain supernova models and the evolution of galaxies over the last ~ 1 Gyr?

   Most everyone is unaware of the great leap forward experimentally on trying to measure this flux, and therefore how real the prospects are for detection. With the exception of SN 1987A, neutrinos have never been detected from outside the Solar System. This is complementary to other techniques (e.g., AGN or GRB neutrinos in IceCube-like detectors, or the GZK neutrinos in ANITA, etc.), any of which could be the first detection of extragalactic neutrinos. Ultimately, we want to see all three types of sources.

   Another related revolution is the improvement in astronomical determinations of the star formation rate history. Recently, using SDSS and other data, this has been well measured up to about $z = 1$. Since the star formation rate fell by almost an order of magnitude between $z = 1$ and $z = 0$, this data is an important measure of galaxy evolution. It has recently been shown by Strigari et al. that the existing bounds on the diffuse supernova neutrino background are already stringent enough to reduce the SDSS-allowed range for the star formation history by about half. It is very impressive that a neutrino bound is competitive with direct optical observations.

What are the benefits of taking this further, to the point of detection? Besides the above, it would also constrain supernova models, both the neutrino emission per supernova and the fraction of supernovae failing and becoming black holes. A measurement of the neutrino spectrum would provide a new constraint for numerical supernova models (and it would only take of order 10 events to compete with the SN 1987A data).

How much further is there to go on the flux, given the uncertainties?

Prospects for experimental progress? What should be done? SK, SK with Gd, KamLAND, UNO or Hyper-Kamiokande. Note that HK would expect one supernova neutrino *per day*, and could see them if backgrounds can be reduced. Raghavan has a proposal (http://www.phys.vt.edu/~kimballton/) as well.

How can such observations test neutrino properties? A few recent papers on neutrino decay tests with these. Dark matter decay or annihilation or other exotic signals could be limited by non-observation.

8. Measurements of neutrino-nucleus cross sections **(Vince Cianciolo @ Oak Ridge)**

   How can we improve low-energy neutrino-nucleus cross section data?

   Neutrino-nucleus cross sections are very poorly known, but they are essential for understanding supernovae, in setting the opacities, affecting the nucleosynthetic yields, and of course in detection. These uncertainties directly affect what we can learn from studying supernova neutrinos, and hence the tests of new physics and neutrino physics discussed above.

   Only the deuteron and carbon have used in controlled experiments, and the errors were large. In the case of carbon, some data at moderate energies (few hundred MeV) remains discrepant with theory predictions. Oxygen, of tremendous practical importance, remains unmeasured. Testing the deuteron cross section is also important regarding the SNO solar neutrino data.

   Muon decay at rest and low-energy beta beams have both been proposed as high-intensity sources of low energy (< 100 MeV) neutrinos.

   Low-energy cross section measurements on a variety of nuclear targets would provide sensitive tests of nuclear models. These improvements would have the direct practical importance mentioned.

   Less obvious is the point that these models are also important for understanding neutrino cross sections at higher energies. In calculations with nuclear models like CRPA, the cross section is evaluated in two steps: first a fundamental interaction which leaves the nucleus in an excited state, and then a statistical model for the decay of this excited state, including modes with particle emission. At higher energies, approaching a GeV, these inelastic modes become more and more important, and there very little available data. Future long-baseline experiments, particularly those operating in off-axis mode (below a GeV, with a need for precision), will need to know more about the inelastic modes to better reconstruct the neutrino energy of each event, especially for small momentum transfer. The better the neutrino energy is known, the better the ability to look for spectral distortions due to oscillations.

   Important to measure neutral-current cross sections too.

   How well can the cross sections be measured, total and differential in charged lepton energy? What about charged vs. neutral current? And inelastic modes, particularly those with neutron emission?

9. Leptogenesis and the origin of the baryon asymmetry **(Hitoshi Murayama @ Berkeley)**

   Are neutrinos a key to the puzzle of the matter-antimatter asymmetry of the Universe?

   Difficulties with baryogenesis scenarios, motivations for leptogenesis.

   How can leptogenesis models be tested? Is it necessary but not sufficient to measure the low-energy neutrino parameters (masses, mixings, hierarchy, Dirac vs. Majorana)? How strong are the connections between low and high energy scales (analogy to connection between the gauge couplings measured in the lab and their unification at the GUT scale?)?

   In particular, what impact, if any, would a long-baseline neutrino experiment measurement of the CP phase δ have on understanding leptogenesis? What is the importance of measuring δ?

How general are models like those of Buchmuller et al., which claim a bound on the light neutrino masses? Or that of Frampton, Glashow, and Yanagida, which connect δ to the sign of the matter asymmetry?

10. Precision big bang nucleosynthesis tests **(Keith Olive @ Minnesota)**

    How can advances in big bang nucleosynthesis test for new physics in the neutrino sector and beyond?

    Many people are under the mistaken impression that BBN hasn't said anything new in a decade, and are not adequately recognizing some of the important developments and future potential.

    First, that CMB results for Ω_b are now very competitive, and are in agreement with results from D/H in quasar absorption line systems. This is an extremely important consistency check.

    Second, that while the scatter is large now, ultimately D/H measurements could become precise enough for a new measure of N_ν, avoiding the potential systematics of ^{4}He.

    Third, neutrino oscillation data now present a coherent picture of active-active oscillations with two large mixing angles. With the possible exception of LSND, there is no call to introduce sterile neutrinos which might affect BBN. Also, unless new relativistic degrees of freedom are introduced, the observed large mixing angles rule out the possibility of hiding a large lepton asymmetry in $\nu_\mu/\bar{\nu}_\mu$ or $\nu_\tau/\bar{\nu}_\tau$.

    What about the future? What will be the impact of improvements of the above points? One important milestone would be a robust limit on ΔN_ν which reaches well below 1 (one extra neutrino, e.g., a thermalized sterile), or 4/7 (an extra light boson). What other qualitative improvements are possible? The question of the role of sterile neutrinos of particularly far-reaching importance. What more can be gained from the BBN-CMB comparison? What if CMB measurements place a precise limit on ΔN_ν?

    What are other observations or data are needed? Nuclear data?

    BBN has been tremendously important in constraining a wide variety of new physics models. What do we stand to gain in neutrino physics or more generally by bringing in the era of precision BBN?

11. Precision cosmic microwave background tests **(Manoj Kaplinghat @ Davis)**

    How can future CMB data make stringent tests of neutrino properties?

    CMB observations have played an undeniably important role in establishing the "precision cosmology," and have begun to have an impact on cosmological tests of neutrino properties. Namely, in combination with large-scale structure data, the best limits on neutrino mass, and in combination with the Hubble constant, a reasonable limit $\Delta N_\nu < 3$ or so.

    But a great deal more CMB data will be taken by MAP, Planck, etc. Will it be enough to qualitatively improve our understanding of neutrino parameters? While particle and nuclear physicists seem to accept the CMB and LSS measurements of most cosmological parameters, they seem to have much more skepticism about limits on neutrino mass. Of course, this is appropriate because of the importance of m_ν. To what extent are the present conclusions robust, and how believable will future results be?

    As for BBN above, in order to make the greatest qualitative difference, the precision on ΔN_ν needs to be brought well below 1. How soon and how reliably can this be done? Given the importance of the sterile neutrino question, due to LSND, a solid answer from CMB would have a significant impact.

    The most interesting question is whether CMB observations can ever reach the sensitivity required to reach neutrino masses as small as $\sqrt{\delta m^2_{atm}}$, so that discovery is "guaranteed" (one neutrino mass in the normal hierarchy, two in the inverted hierarchy, and three if the scale is above $\sqrt{\delta m^2_{atm}}$). Given the importance of neutrino mass, and the vast resources being allocated to the next decades of terrestrial experiments, how do the expenses and difficulties of a requisite CMB experiment stack up?

    Discovery of neutrino mass with the CMB could establish a very important guide and foil for the terrestrial neutrino mass experiments, telling them where to look. If neutrino mass were discovered cosmologically, but not seen in neutrinoless double decay, that could shed light on the Dirac vs. Majorana question. Depending on the measured value of neutrino mass, one might be able to distinguish the normal, inverted, and degenerate hierarchies. Can these neutrino questions help motivate future CMB missions?

Of course, neutrino "mass" here means an appropriate sum of neutrino mass eigenstates. Key point is that cosmology doesn't care about Dirac vs. Majorana. Nor the neutrino mixing angles, especially U_{e3}, the smallness of which makes both tritium decay and neutrinoless double beta decay experiments much more difficult.

12. NEUTRINO MASS AND LARGE SCALE STRUCTURE **(Scott Dodelson @ Fermilab)**

    Can future large scale structure studies measure neutrino mass?

    Already, the CMB + LSS limits on the sum of neutrino masses are the best of any technique. It is important to get the sensitivity down to the scale of guaranteed discovery, e.g., about $\sqrt{\delta m^2_{atm}}$. Even before that point, there is a qualitative difference if the limit is well below 1 eV, since that is the mass scale of LSND (this depends on whether a potential sterile neutrino is thermalized before BBN).

    Measuring the sum of the neutrino masses of unquestionably of the highest importance, for a wide variety of reasons.

    Neutrinos are one of the known components of the dark matter. There is a parameter degeneracy with the spectral index n and its possible running n', and those are important for testing models of inflation (unlike Ω_m, there are specific predictions from theory). And those those parameters can have an important impact on galactic halo and subhalo studies (e.g., Koushiappas, Zentner, and Walker, astro-ph/0309464, have shown that varying these affects $\chi\chi \rightarrow X\gamma$ searches dramatically). If neutrino mass is discovered cosmologically, it also tests the fact that the relic neutrinos are present, and in the expected numbers (changes in N_ν, large lepton asymmetries, potential new interactions of neutrinos, etc.)

    The actual neutrino mass scale is crucial for models that seek to explain why they are so light, since it determines if the hierarchy is normal, inverted, or degenerate. As noted in the CMB section, a comparison of cosmological and laboratory measurements could shed light on the Dirac vs. Majorana question, or at least give the experimentalists sensitivity targets for their designs. Sterile neutrinos can also potentially affect the measured neutrino mass sum.

    Given the importance of these questions, how high of a priority should the appropriate LSS measurements get? How much weight do these issues add to the motivation of new experiments?

    What are the prospects for progress with LSS data, present and future? What are the possible techniques (e.g., weak lensing, Lyman alpha, halo substructure, etc.)? Prospects for SNAP weak lensing survey, LSST, LOFAR, other? How robust will these measurements be? What will it take to convince particle and nuclear physicists of the results?